STIMULUS EFFECTS ON BEHAVIOR ALLOCATION IN THREE-ALTERNATIVE CHOICE

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Six pigeons were trained on three-alternative concurrent variable-interval schedules that were available through a switching response and were signaled by colored stimuli. The discriminative stimuli for two of the schedules were always 560 nm and 630 nm, but the stimulus signaling the third alternative was varied across conditions over seven levels between these colors. For each third-alternative stimulus condition, the relative frequency of reinforcers was varied over three conditions with 4:1 and 16:1 reinforcer ratios between each pair of alternatives. The distribution of responses between the alternatives was dependent jointly on the third-alternative reinforcer rate and on the disparity between the stimulus signaling the third alternative and those signaling the other alternatives. A generalized matching approach was unable to provide invariant measures of the discriminability between constant stimuli, but a contingency-discriminability approach provided excellent fits and sensible and invariant stimulus discriminability measures.

Key words: concurrent schedules, choice, stimulus control, contingency discriminability, generalized matching, key peck, pigeons

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Davison and McCarthy (1994) investigated performance in three-alternative concurrent variable-interval (VI) schedules arranged in a switching procedure in which the alternatives were signaled by colored stimuli. One alternative was always signaled by 560-nm light, and another was signaled by 630-nm light. The third alternative was signaled either by 600-nm light or, in other conditions, by 623-nm light. The procedure had two unusual features not normally found in the typical two-alternative concurrent schedule: First, every changeover was followed by a 3-s blackout (while the monochromator selected the next color); second, the schedule and stimulus produced by a changeover response, and following a reinforcer, were probabilistically determined, with each alternative (including that switched from) occurring with equal probability. This latter procedure was used in order that the subjects should not be able to discriminate the upcoming schedule on the basis of the reinforcer rates currently in effect (see Alsop & Davison, 1992). Davison and McCarthy found that the choice between pairs of constant schedules in this procedure was affected by the rate of reinforcers obtained

on the third alternative. Davison and McCarthy modeled their results using an extension of a model of two-alternative concurrent-schedule choice suggested by Davison and Jenkins (1985) and Vaughan and Herrnstein (1987). This model was developed explicitly to account for less-than-perfect discrimination between the stimuli signaling the alternatives, and it contains parameters (p_{ij}) that measure the confusability of these stimuli. A value of p of zero indicates no confusion between the stimuli, and higher values indicate increasing degrees of confusion. In a three-alternative choice, complete confusion (no discriminability between the response alternatives) is given by $p = .33$ between every pair of alternatives. The original model was also modified so as to accept a punishment factor (w) that represented the loss of reinforcers occasioned by switching between alternatives and hence producing the short blackout. They used the following model:

$$\frac{B_i}{B_k} = \frac{R_i - p_{ik}R_i - p_{ij}R_i + p_{ik}R_k + p_{ij}R_j - w}{R_k - p_{ik}R_k - p_{jk}R_k + p_{jk}R_j + p_{ik}R_i - w},$$

(1)

where B refers to responses emitted and R refers to reinforcers obtained on the three (i, j, k) alternatives. Equivalent equations apply to the other two binary choices (i vs. j and j vs. k) in the three-alternative situation. This model provided a good fit to their data, and provided sensible estimates of the p_{ij} and w constants.

Obtained reinforcers

R	G	Y
160	40	10

Perceived reinforcers

G	R	Y	R	G	Y	R	Y	G
16	128	16	4	32	4	1	8	1
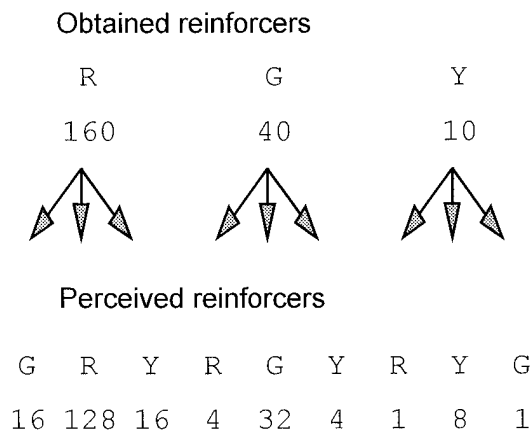
Matching law (Obtained reinforcers):

$B_r/B_g = 160/40 = 4{:}1$

Confusion model (Perceived reinforcers):

$B_r/B_g = (128+4+1)/(32+16+1) = 2.71{:}1$

Fig. 1. A didactic figure showing the operation of Equation 1 compared with the operation of the strict matching law. Because of confusion between the stimuli signaling the alternatives (here, all p values are .1), reinforcers delivered in the presence of the stimuli are confused between the alternatives, predicting less extreme differential responding than is predicted by strict matching.

Equation 1 operates in the following way: Some reinforcers obtained in the presence of a stimulus (say Stimulus i) reinforce responses to that color, but, because of confusion between the signaling stimuli, some of these food deliveries apparently also reinforce responses to other (j, k) colors. If p_{ij} is the discriminability between Stimuli i and j, then $R_i p_{ij}$ reinforcers will be lost from R_i and will be added to R_j. Similarly, $R_j p_{ij}$ reinforcers will be lost from R_j and gained by R_i. The equivalent process will occur for reinforcers delivered in the presence of Stimulus j and Stimulus k. The process is diagrammed in Figure 1. Thus, the numerator of Equation 1 provides the net reinforcers apparently obtained by the subject in the presence of Stimulus i, and the denominator provides the same for Stimulus k. Finally, the equation assumes that behavior-allocation ratios strictly match ratios of the apparent reinforcer fre-

quencies attributed to each source by the subject rather than the obtained reinforcer ratios measured by the experimenter.

Davison and McCarthy's (1994) model (Equation 1) accounts for the interaction of stimuli and reinforcers in controlling choice. The implications of their model can be exemplified in the following way: Suppose we arrange concurrent schedules with 2 and 0.25 reinforcers per minute available on two alternatives in a switching-key concurrent-schedule procedure, each signaled by red or green light. Subjects that have reasonable psychophysical sensitivity in this color region will respond at very different rates to the two stimuli. However, if a third alternative is also made available, the effect on the behavior allocation between the original two stimuli will depend on both the third-stimulus value and the third-stimulus reinforcer rate. There are four extreme possibilities: (a) A reinforcer rate lower than two per minute and a stimulus close to red will decrease the apparent reinforcer rate in red, leading to a fall in the red-green response ratio. (b) A reinforcer rate lower than 0.25 per minute signaled by a stimulus close to green will decrease the apparent reinforcer rate in green, leading to an increase in the red-green response ratio. (c) A reinforcer rate higher than two per minute and a stimulus close to red will increase the apparent reinforcer rate in red, and the response ratio should increase. (d) A reinforcer rate higher than 0.25 per minute signaled by a stimulus close to green will increase the apparent green reinforcer rate and decrease the response ratio. Response-rate differentials, then, can presumably be increased by the existence of either higher or lower alternative reinforcer rates, depending on the relative value of the stimulus that signals this alternative. Thus, in any natural or experimental situation, if the behavior allocation between the alternatives changes in this way, it is not possible to determine a priori what combination of stimulus and reinforcement value has caused the change.

The present experiment was designed to complement the experiment reported by Davison and McCarthy (1994) and to validate their proposed model (Equation 1). In the present experiment, the focus is on varying stimuli rather than reinforcers. As in Davison and McCarthy's study, the colors signaling

two of the alternatives were fixed at 560 and 630 nm. In the present experiment, the color signaling the third alternative was varied from 563 nm to 627 nm in seven steps across sets of conditions. For each of these colors, three conditions were arranged, all of which had differing reinforcer rates on the three alternatives in some combination of the ratio 16: 4:1. The aim of this design was to provide sufficient data to obtain estimates of all the 15 p_{ij} values (with a composite value of w) using multidimensional nonlinear regression. These 15 p_{ij} values arise from (a) a single value for the confusion between 560 and 630 nm, (b) seven pairwise values for the confusion between 560-nm and the intermediate X-nm values, and (c) seven pairwise values for the confusion between 630-nm and the intermediate X-nm values. It was hoped that these values could be related to the known psychophysical sensitivity to color of the pigeon visual system (e.g., Wright, 1972).

The present experiment also allows a second assessment of the correctness of Davison and McCarthy's (1994) model. If the model is correct and the confusability parameters are mutually independent, the confusion measure between the two unchanged stimuli (560 and 630 nm) should not change in any systematic way as the third-stimulus value is moved between these unchanged stimulus values. This requires the determination of the confusability between the 560- and 630-nm stimuli for each value of the intermediate stimulus X, and hence fits of the model to the data obtained from the three reinforcer-ratio variations in the presence of each X-nm intermediate stimulus. Finally, confusion values between stimuli should be ordinally related to stimulus (nanometer) differences, at least after taking account of areas of high and low color sensitivity.

METHOD

Subjects

Six homing pigeons, numbered 101 to 106, were maintained at 85% ±15 g of their free-feeding body weights. The subjects were the same subjects as those used by Davison and McCarthy (1994). Following that experiment the subjects were trained on the procedure used in the present experiment over 22 con-

ditions, except that two of the three reinforcer rates were always equal. This procedure did not provide sufficient systematic variance for a clear data analysis, and so the present procedure was adopted.

Apparatus

The apparatus was the same as that used by Davison and McCarthy (1994). The experimental chamber was 310 mm wide, 340 mm deep, and 310 mm high, and was fitted with an exhaust fan for ventilation and to help mask external noise. On one wall of the chamber were three response keys, 20 mm in diameter, 150 mm apart, and 250 mm from the grid floor. These keys required a force of about 0.1 N to register an effective peck. Beneath the center key was a food hopper, located 70 mm from the grid floor. During reinforcement, which was 3-s access to wheat, the hopper was raised and illuminated for 3 s, with all other chamber lights extinguished. Only the left and center keys were used in this experiment. The left key, when available, was illuminated white. The center key, which was transparent, had a light-fiber termination 2 mm behind the key that provided a 3-mm patch of light of selected colors. A 0.1-A 28-Vdc houselight provided general illumination.

The center-key color was produced by an Oriel Corporation Model 7240 monochromator with a 100-W quartz-halogen bulb, a 1,200 lines per millimeter grating, and a 280-micron fixed slit. This provided an approximate bandpass of 2 nm. There was no control of light intensity. The monochromator setting was controlled by a stepping motor controlled by a dedicated microprocessor.

Procedure

As in Davison and McCarthy's (1994) study, schedules were arranged according to a switching-key procedure, with the white side key as the switching key and the center key as the main key. One of three colors was displayed on the center key, and each color was associated with its own VI reinforcement schedule. Two of the center-key colors were 560 and 630 nm, and the third was a color of a nanometer value intermediate between these two colors. This color is designated X. The schedules arranged reinforcers with a fixed probability per second of .028 per second (an exponential VI 35.7-s schedule), and, once set up, they were allocat-

Condition number	Probability of reinforcement allocation			Nm value of X	Sessions
	560	630	X		
53	.762	.191	.048	615	22
54	.191	.048	.762	615	22
55	.048	.762	.191	615	24
56	.762	.191	.048	627	22
57	.191	.048	.762	627	22
58	.048	.762	.191	627	35
59	.762	.191	.048	570	21
60	.191	.048	.762	570	25
61	.048	.762	.191	570	22
62	.762	.191	.048	623	21
63	.191	.048	.762	623	20
64	.048	.762	.191	623	21
65	.762	.191	.048	619	22
66	.191	.048	.762	619	22
67	.048	.762	.191	619	22
68	.762	.191	.048	600	21
69	.191	.048	.762	600	21
70	.048	.762	.191	600	20
71	.762	.191	.048	563	24
72	.191	.048	.762	563	23
73	.048	.762	.191	563	22

ed according to set probabilities (Table 1) to one of the three alternative schedules. A response to the white changeover key immediately turned off the white key and the color on the center key, and they remained off for 3 s. This period was required to allow the monochromator to select the next center-key color. Following the blackout of the keys (but not the houselight), the next stimulus and associated schedule were provided. In all parts of the experiment, the new color and schedule were selected randomly in order that there could be no discriminative control over the performance by the reinforcer rates. Thus, in all parts, there was a .33 probability that the same stimulus and schedule combination would be presented after a switch. Exactly the same procedure was used to select the stimulus and schedule after a reinforcer had been obtained: That is, after a reinforcer, the prevailing stimulus and schedule were presented with equal probabilities.

Sessions were arranged daily and ended in blackout after 45 min had elapsed or after 40 reinforcers had been collected, whichever

event occurred first. The sequence of experimental conditions is shown in Table 1. The design of the experiment was thus to arrange over conditions a number of stimulus values in the range of 563 to 627 nm as the discriminative stimulus signaling the third alternative (X in Table 1), and for each value of X to arrange a range of pairwise reinforcer ratios in which one was four times, and the other was 16 times, the lowest reinforcer rate.

Sessions were arranged in each experimental condition until two stability criteria had been met. The first criterion required that the median 560-nm relative response rate (pecks on the 560-nm alternative divided by total pecks to all alternatives) over five sessions was not more than 5% different from the median from the previous set of five nonoverlapping sessions. When this criterion had been met five, not necessarily consecutive times, that subject had met the second criterion. When all subjects had met the second criterion, the experimental condition was changed. Stability thus required 14 sessions at minimum, although more were normally required (Table 1).

In each session, the number of responses to each of the three alternatives, the time spent responding to the alternatives (from changeover to changeover, excluding blackout time), and the numbers of obtained reinforcers were recorded. The data analyzed were from the last five sessions of each experimental condition.

RESULTS

The data obtained from each subject in each condition, summed over the last five sessions of training, are shown in the Appendix. Figure 2 shows pairwise log response ratios for each condition of the experiment. Group data are shown to save space, and these are fully representative of the performance of the individual subjects. The top panel shows performance on the 560- versus 630-nm alternatives as a function of the nominal reinforcer ratio as the nanometer value of the third alternative was changed. When the reinforcer ratio between these alternatives was 16:4 (with the third alternative 1), there was little change in log response ratios with the nanometer value of the third alternative. However, when the reinforcer ratio was 4:1 (third alter-
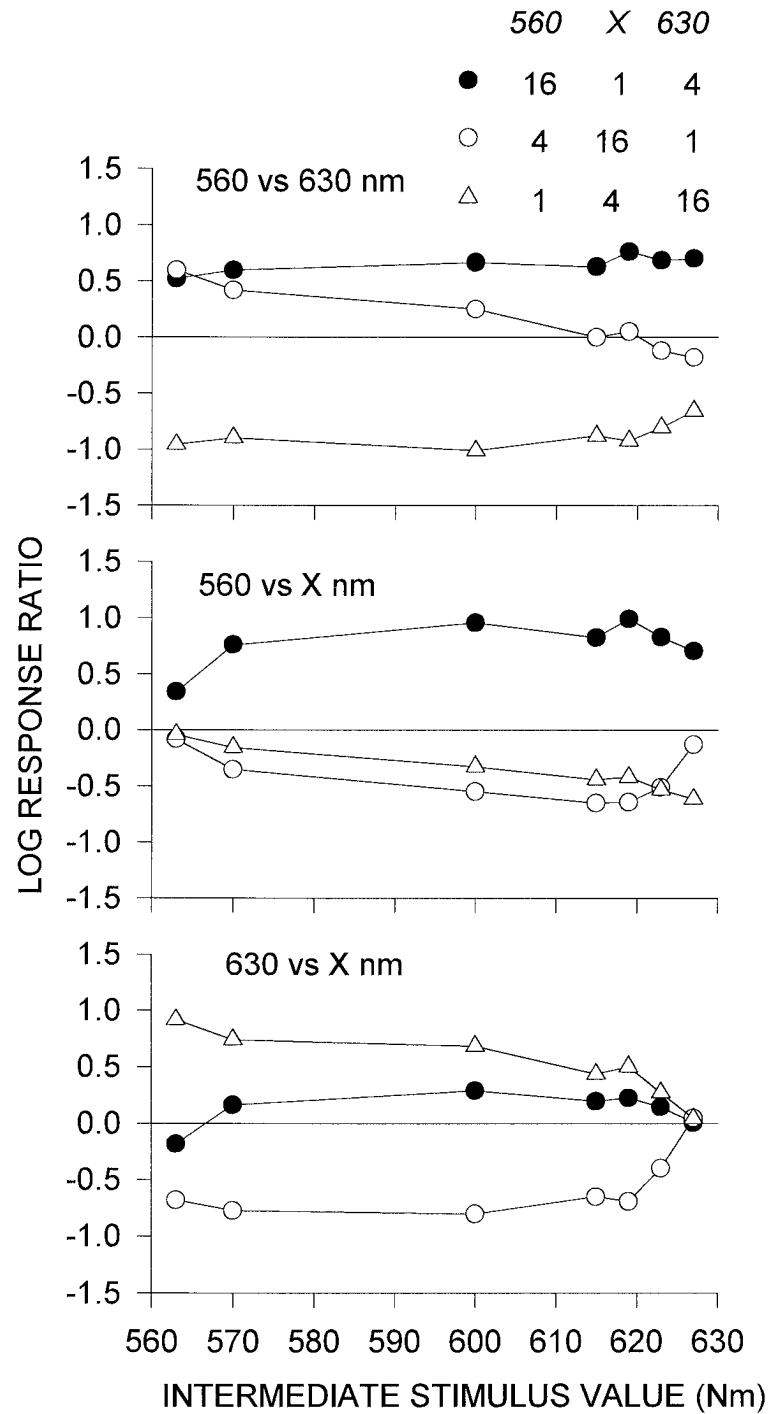
Fig. 2.   Log response ratios between the three pairwise alternatives when the intermediate stimulus value was varied from 563 to 637 nm. The data have been summed over the 6 subjects, but are representative of the individual subjects. The parameters above the figure show the reinforcer-rate ratios between the two alternatives.

native 16), log response ratios decreased substantially as the nanometer value of the third alternative was increased from 563 to 627 nm. This can be understood as the high third-alternative reinforcer rate becoming progressively more confused with the 560-nm alternative when X was close to 560 nm, and more confused with the 630-nm alternative when X was close to 630 nm. Finally, when the reinforcer ratio was 1:16 (with the third alternative 4), response ratios increased with increasing nanometer values of X, as the third alternative moved from being more confused with the 560-nm alternative to being more confused with the 630-nm alternative. It is clear, then, that response ratios between alternatives with high reinforcer rates were affected by the variation of X signaling a low reinforcer rate less than were lower reinforcer-rate ratios affected by the variation of X associated with high reinforcer rates.

The second panel shows log response ratios between the 560- and X-nm alternatives. As would be expected, the 16:1 reinforcer ratio produced a strong preference for the former alternative, whereas the 4:16 and 1:4 ratios produced a preference for the latter alternative. There is evidence that log response ratios for 16:1 and 4:16 were most extreme when the third-alternative stimulus values were intermediate. In the 16:1 case, this is because, when the intermediate stimulus value was close to the color (560 nm) signaling the highest reinforcer-rate schedule, stimulus confusion would decrease the apparent reinforcer rate in the presence of that stimulus. When the intermediate stimulus was close to 630 nm, stimulus confusion would effectively increase the apparent rate of reinforcers at 630 nm. In the 4:16 case, when X was close to 560 nm, these two alternatives would be only marginally discriminable, and the rates of reinforcers on them would appear similar. When X was close to 630 nm, the high reinforcer rate on this alternative would be degraded by the low rate of reinforcement on the third alternative. In the 1:4 case, when X was close to 560 nm, again the reinforcer rates obtained from the 560-nm and X-nm alternatives would be confused. When X was close to 630 nm, X would be confused with the third alternative with the highest reinforcer rate, producing a greater preference for X. Thus, the log response ratio

for 560 versus X nm at a 1:4 scheduled reinforcer ratio should, and does, show a progressive increase in preference to the X alternative as X is moved from 563 to 627 nm.

Finally, the lowest panel of Figure 2 shows performance on the 630-nm versus X-nm alternatives. Log response ratios in the 16:4 reinforcer-ratio schedules declined as X became closer to, and more confusable with, the 630-nm alternative. Log response ratios in both the 4:1 and 1:16 reinforcer-ratio conditions also moved to indifference for the same reason when X moved closer to 630 nm. However, when the 4:1 ratio was close to the third alternative (560 nm), the apparent reinforcer rate on X would be increased by confusion with the high reinforcer rate on 560 nm, leading to a decrease in the log response ratio. For the 1:16 ratio, moving X closer to the 560-nm alternative would have decreased the apparent reinforcer rate on X, and the log response ratio, as expected, showed an increase.

DISCUSSION

It is evident from Figure 2 that, as Davison and McCarthy (1994) showed, both stimuli and reinforcer rates interact in their effects on log response ratios. The question to be answered now is whether or not existing descriptions of concurrent-schedule performance can adequately account for these quantitative findings.

Generalized Matching

Figures 3 to 5 show a generalized matching analysis of the performance of individual subjects. The generalized matching law (Baum, 1974) is written

$$\log \frac{B_1}{B_2} = a \log \frac{R_1}{R_2} + \log c, \qquad (2)$$

where the variables B and R are the same as in Equation 1. The parameter a is called sensitivity to reinforcement (Lobb & Davison, 1975), and it measures the change in log ratio performance relative to the change in the log ratio of the reinforcer rates. The parameter $\log c$ is called bias, and it measures any constant proportional preference for one or the other alternative when R_1 and R_2 are varied. In Equation 2, as in Equation 1, R_1 and R_2 are measured reinforcer frequencies ob-

Fig. 3.   Sensitivity to reinforcement (*a* in Equation 2) for the 560- versus 630-nm alternatives for the 6 subjects as a function of the value of the intermediate stimulus. Sensitivity values were obtained by fitting Equation 2 to the three data points for each intermediate-stimulus value.

tained by the subject. The generalized matching law has commonly been found to be an excellent fit to both two- and three-alternative concurrent-schedule performance (e.g., Davison & McCarthy, 1988).

In Figures 3 to 5, sensitivity-to-reinforcement values were calculated by fitting Equation 2 to the three data points from each triplet of conditions with the same third-alternative stimulus value. For the 560-versus 630-nm choice (Figure 3), the performance showed sensitivity values ranging from some overmatching (sensitivity greater than one) for Bird 101 to some consistent undermatching for Bird 104. In general, there

seemed to be no consistent trend in sensitivity values with changes in the intermediate-stimulus value. Figure 4 shows sensitivities for the 560- versus *X*-nm choice. As *X* was increased from 563 to 627 nm, there was a clear increase in measured sensitivity as the stimuli signaling the alternatives became more disparate. The opposite trend is shown in Figure 5 for the 630- versus *X*-nm choice. Here, sensitivity fell as the value of *X* became closer to 630 nm, indeed falling to close to zero for all subjects when *X* was 627 nm. Comparing Figures 4 and 5, it seems that 560 nm was more discriminable from 563 nm than was 627 nm from 630 nm. The results for both 560 versus
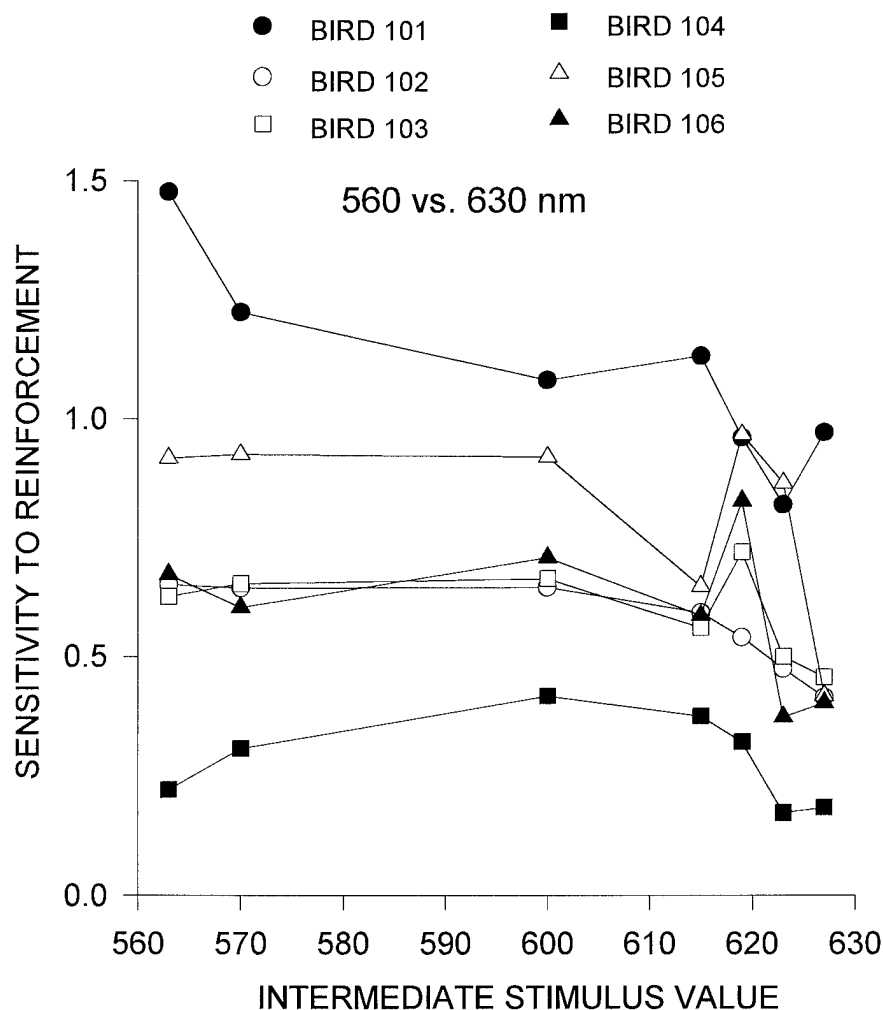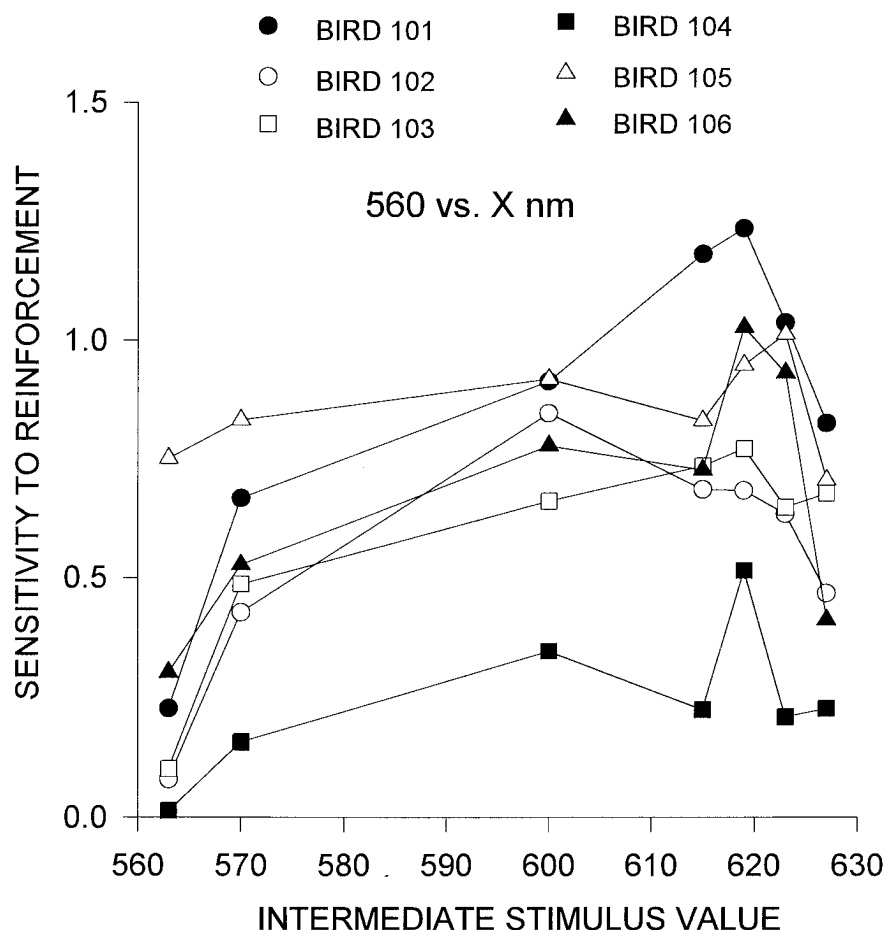
Fig. 4.   Sensitivity to reinforcement (a in Equation 2) for the 560- versus X-nm alternatives for the 6 subjects as a function of the value of the intermediate stimulus, X. Sensitivity values were obtained by fitting Equation 2 to the three data points for each intermediate-stimulus value.

X nm and 630 versus X nm correspond to those reported for changing stimulus disparity in a two-alternative concurrent schedule by Miller, Saunders, and Bourland (1980).

From Figures 3 to 5, it is evident that no single value of sensitivity to reinforcement could describe the present data. We could, of course, use sensitivity to reinforcement as an index of stimulus discriminability, as has been done by White, Pipe, and McLean (1984) for multiple schedules, and de facto by Miller et al. (1980). However, the evident interaction of stimulus disparity and reinforcer rate in determining the value of a precludes this being a suitably independent measure. This interaction was shown by Davison and McCarthy (1994), and is best shown in the present data in the top panel of Figure 2. For the

constant disparity between 560 and 630 nm and for a constant reinforcer ratio of 4:1, response ratios fell with the increasing value of X from strongly positive (implying an a value of close to one) to a negative value (implying a negative sensitivity). Similarly, in the choice between 560 nm and X nm (Figure 4), sensitivity to reinforcement showed a strong positive trend as X was varied from 570 nm to 620 nm. Thus, no single value of a can be associated with a constant stimulus disparity or a constant reinforcer ratio.

Contingency Discriminability

Equation 1 was fitted to the present data in two ways. First, we fitted the model to each of the seven triplets of conditions with differing relative reinforcer frequencies arranged
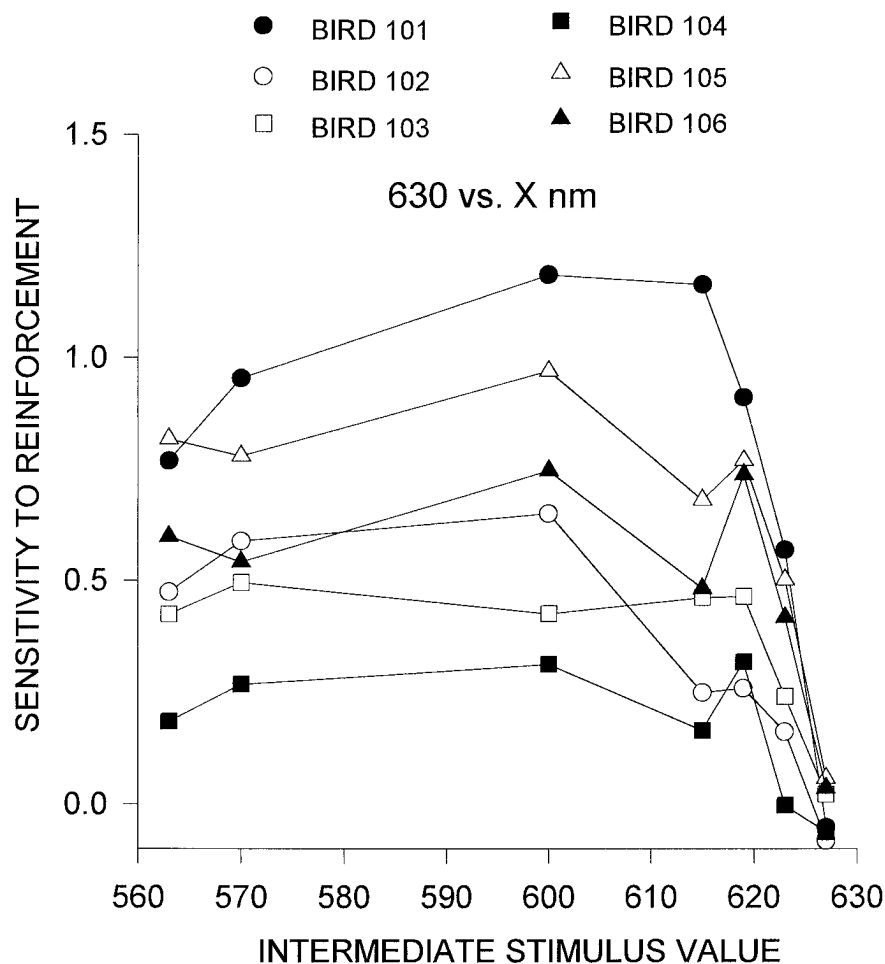
Fig. 5. Sensitivity to reinforcement (*a* in Equation 2) for the 630- versus *X*-nm alternatives for the 6 subjects as a function of the value of the intermediate stimulus, *X*. Sensitivity values were obtained by fitting Equation 2 to the three data points for each intermediate-stimulus value.

with the same stimulus value of *X*. This required nonlinear regression, and estimates of the three confusion parameters (p_{ij}, p_{ik}, p_{kj}) were obtained using an optimization procedure in Quattro-Pro for Windows®. For each triplet, we found the values of the three parameters that would minimize the squared deviations between the obtained log response ratios and those predicted from the log form of Equation 1. Because there were only nine such data points available (three pairwise comparisons in each of three conditions), we did not attempt to find a value for *w* in Equation 1, and instead set this to zero. This should be satisfactory for all subjects except Bird 101, which occasionally showed over-

matching. Estimated parameters were constrained to be equal to or greater than zero, because negative confusabilities cannot be allowed in the model given by Equation 1.

For the 6 birds, the mean and range of percentages of variance accounted for by the fits were 87% (81% to 93%), 96% (88% to 99%), 91% (82% to 99%), 93% (84% to 98%), 96% (92% to 99%), and 95% (83% to 99%). The fits were thus good, but it must be recalled that three unknown parameters were being fitted using only nine data points.

Figure 6 shows confusability parameter estimates for the 560- versus 630-nm alternatives as a function of the stimulus value of the *X* alternative. On a nonparametric trend test

Fig. 6. Confusion indices (Equation 1) for the performance on the 560- and 630-nm alternatives for each individual subject as a function of the stimulus value of X. The values were obtained by fitting Equation 1 to the three conditions (nine data points) available for each intermediate-stimulus value arranged.

(Ferguson, 1971), these values showed no significant trend with the value of X ($N = 6$ subjects, $k = 7$ conditions, $z = 0.74$, $p > .05$) and were generally small, indicating little confusion between the alternatives. However, Bird 104 did consistently show quite large estimates of confusability. Confusability estimates for the 560- versus X-nm alternatives are shown in Figure 7 as a function of X. If the model is ordinally correct, we would expect
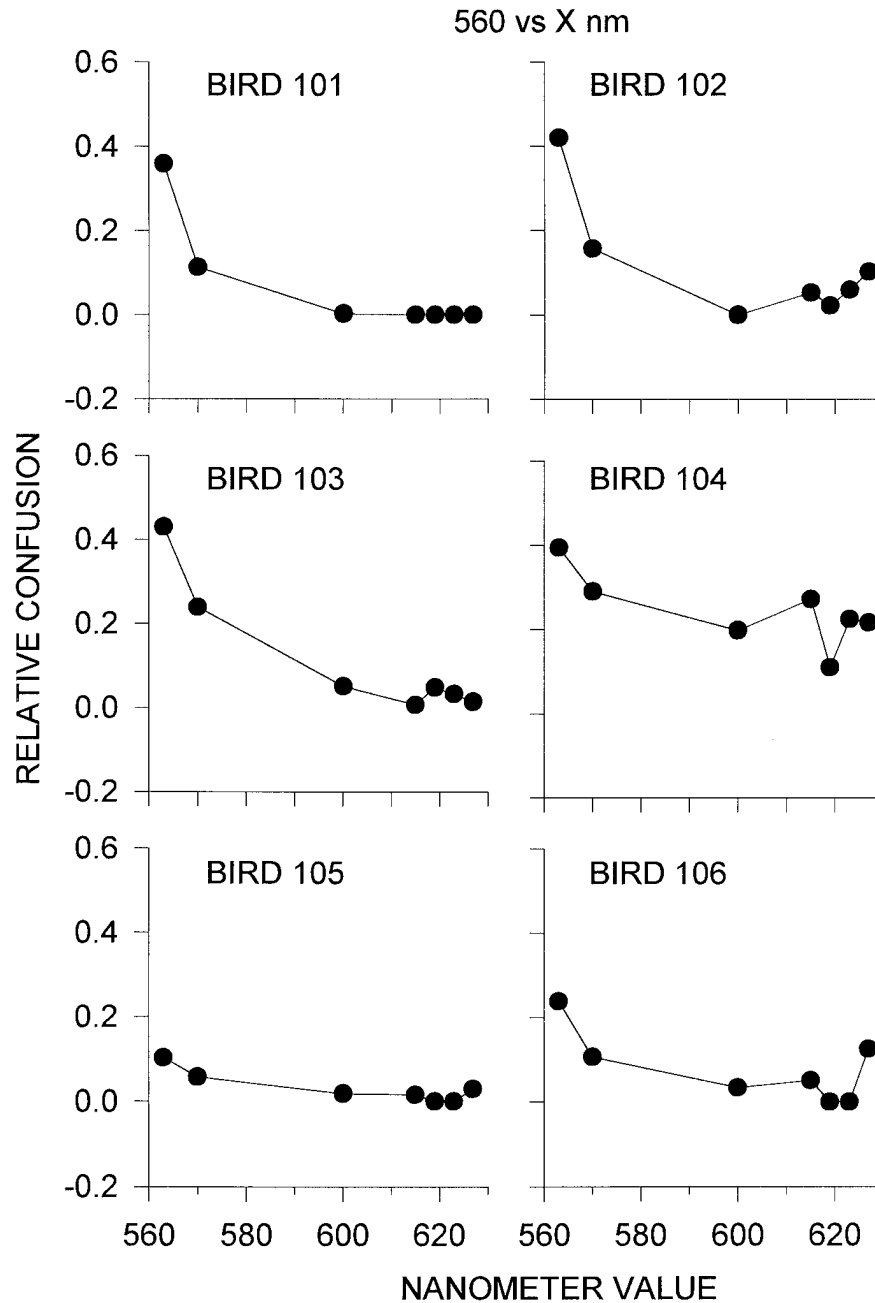
Fig. 7. Confusion indices (Equation 1) for the performance on the 560- and X-nm alternatives for each individual subject as a function of the stimulus value of X. The values were obtained by fitting Equation 1 to the three conditions (nine data points) available for each intermediate-stimulus value arranged.

confusability estimates to fall as the disparity between 560 and X nm increased. This indeed is what occurred, with near-monotonic decreasing trends in confusability to low levels similar to those for 560 versus 630 nm when X was close to 630 nm (on a nonparametric trend test, $z = -3.92$, $p < .05$). Bird 104 showed a similar higher degree of confusability to that shown in Figure 6. Figure 8 shows confusability estimates from the X-ver-
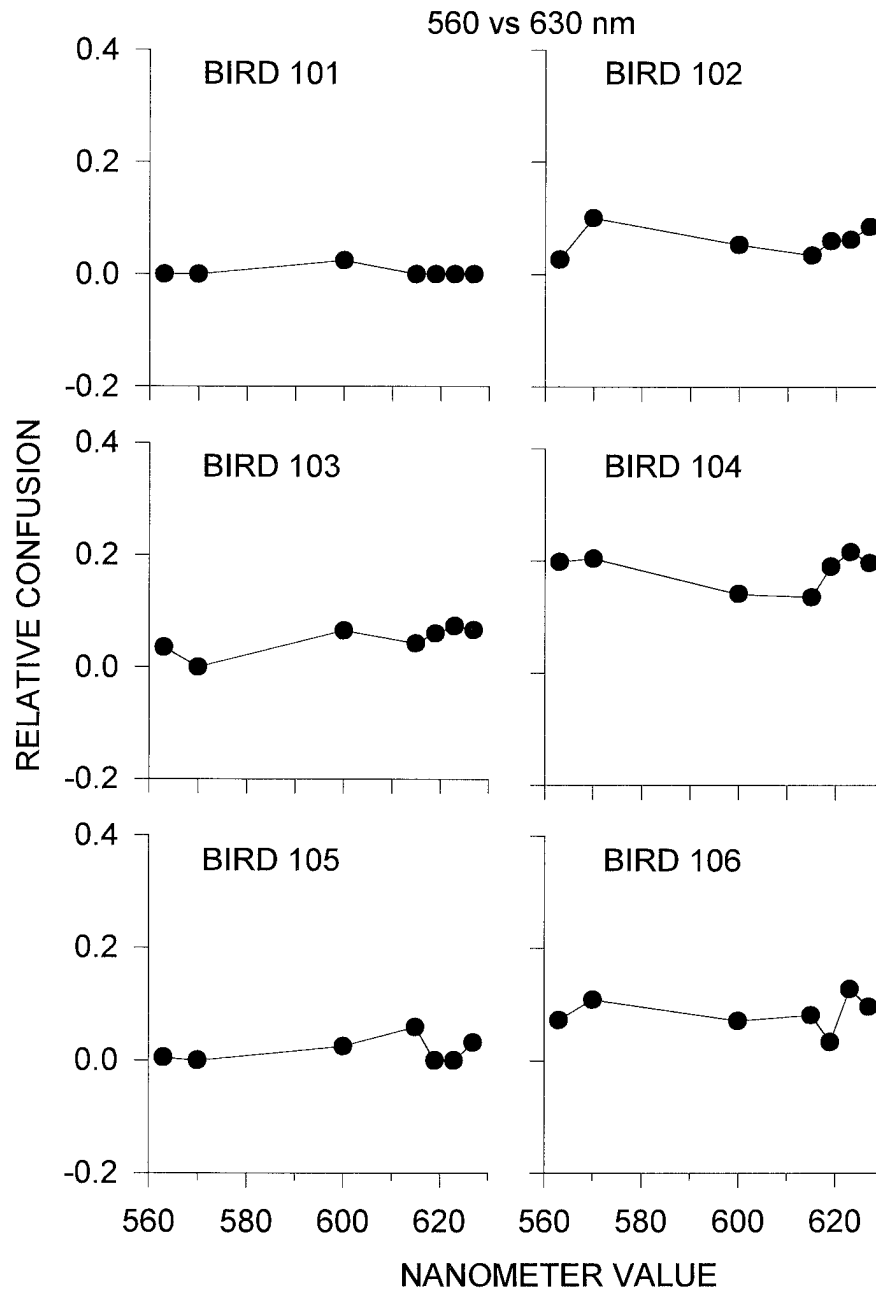
X vs 630 nm
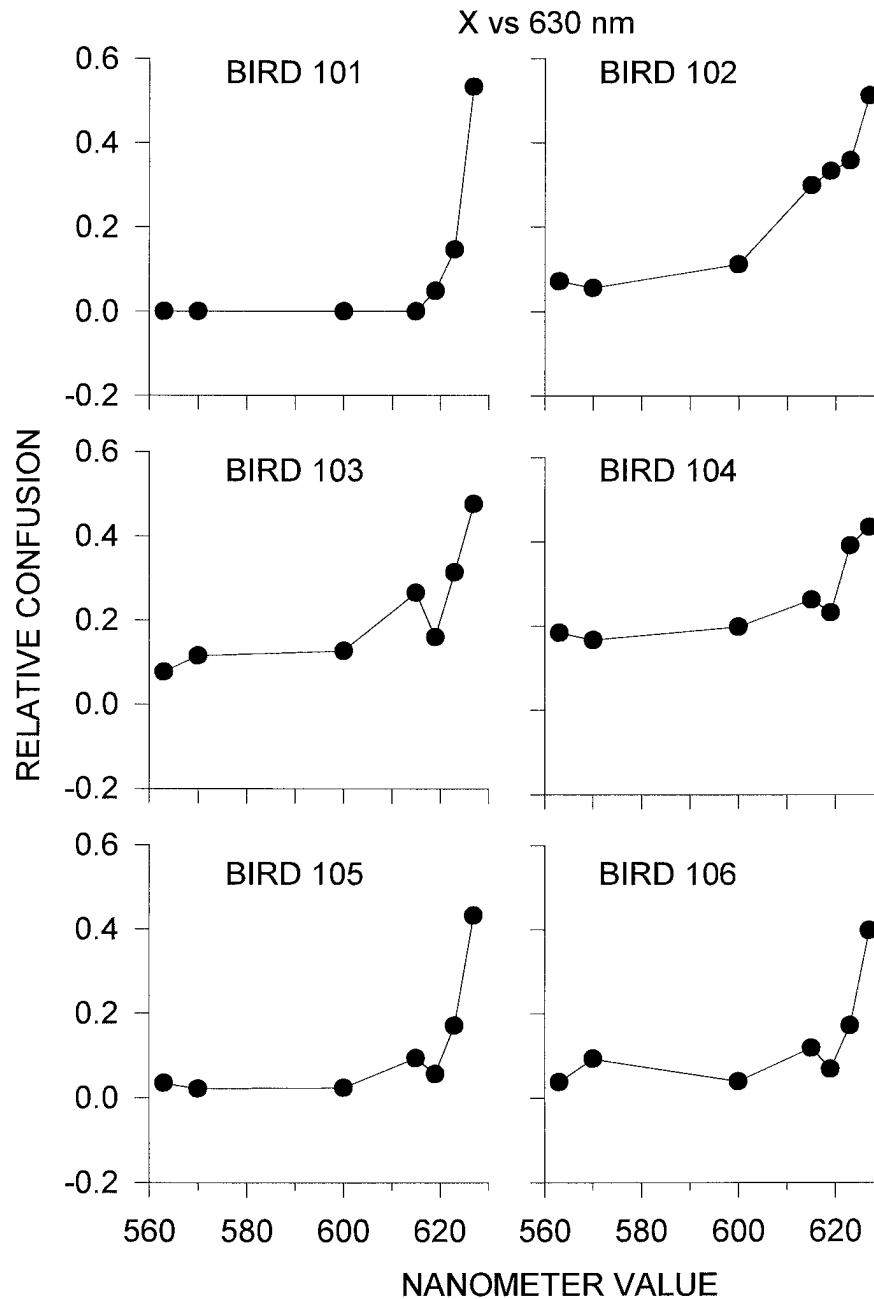
Fig. 8.   Confusion indices (Equation 1) for the performance on the 630- and X-nm alternatives for each individual subject as a function of the stimulus value of X. The values were obtained by fitting Equation 1 to the three conditions (nine data points) available for each intermediate-stimulus value arranged.

sus 630-nm stimulus alternatives. As expected, estimates of confusability increased from a low level when X was close to 560 nm to a high level when it was close to 630 nm. This increase was significant on a nonparametric trend test ($z = 6.13$, $p < .05$). A comparison of Figures 7 and 8 shows that in every individual, confusability estimates were greater between 627 and 630 nm than between 560 and 563 nm.

This analysis (Figure 6) has shown that the confusability estimates between 560 and 630 nm were unaffected by the stimulus value of the third alternative. This finding is important for the validation of the model (Equation 1). This result allows a fit to be done to Equation 1 across all conditions of the experiment using a single value for the discriminability of the 560- versus 630-nm alternative. This fit was carried out using all 63 log pairwise response ratios, and allows the estimation of the other 16 p_{ij} parameters using the same procedure as described above. The obtained confusability estimates are shown in Figure 9 as a function of the nanometer value of X for each individual subject. The changes in confusability estimates obtained from this analysis were very similar, both in terms of trends and levels, to those obtained from the separate analysis of performance in the presence of each of the X-nm stimuli. Again, for all subjects, confusabilities between 627 and 630 nm were higher than those between 560 and 563 nm.

The zero confusability parameter estimates for Bird 101 in Figures 7, 8, and 9 result from this subject's tendency to overmatch. Thus, for this subject, it is clear that a nonzero value of the punishment parameter w is likely to be required. An analysis of the performance of this bird inclusive of the w parameter is presented later.

The confusion parameters shown in Figure 9 were used to make predictions of all pairwise log response ratios from all conditions, and these data are shown as a function of the predictions in Figure 10. It is clear from Figure 10 that, for 5 of the 6 subjects (excluding Bird 101), prediction of the 63 data points by Equation 1 was very accurate, with more than 92% of the data variance accounted for by the model. The straight lines in Figure 10 were fitted between the obtained and predicted data by linear regression. For perfect prediction, these lines would have a slope of one and a zero intercept. As can be seen, for Birds 102 to 106, these fitted lines have slopes very close indeed to one, and intercepts close to zero. There appear to be no systematic deviations of any of the pairwise choice comparisons from the lines of best fit.

Bird 101's performance was less well predicted, although 88% of 63 data points is, in fact, highly significant. As mentioned before,

this subject was the only subject to show any evidence of overmatching, and overmatching in the confusion model (Equation 1) can be predicted only if there are some subtractive punishing effects (see Davison & McCarthy, 1994) as well as additive positive reinforcing effects in the situation. This implies that, for Bird 101, the value of w in Equation 1 was greater than zero. The results of an analysis that incorporated w are shown in Figure 11. The best fitting value of w was 5.53 reinforcers over the five sessions of data used, just over one reinforcer per session. The upper panel shows the obtained confusability values in the same way as in Figure 9. Comparing these with those shown in Figure 9 for Bird 101, although the overall shape of the functions is similar, the confusion estimates did not absorb at values of zero as they did for the analysis excluding w, and the with-w estimates are more similar to those for other subjects. However, the log response-ratio predictions (lower panel of Figure 11) were not clearly any better than those from the analysis excluding w (Figure 10), and the percentage of variance accounted for was the same. Thus, on the grounds of parsimony, in terms of variance accounted for, the model excluding w is to be preferred. However, the nonzero estimates of most confusion parameters in the analysis with w argue for the inclusion of w in the model.

How well do the confusability parameters obtained from the present data fit with what is known about the psychophysics of the pigeon's color vision system? Wright (1972) provided detailed data that clearly showed a region of high psychophysical sensitivity to color at about 600 nm, with lesser sensitivities each side of this point. Because of their disparity, we would expect, and found (Figure 6), very low confusability estimates between these nanometer values. We would also expect that stimuli around 600 nm would be highly discriminable from both 560- and 630-nm stimuli, and this was indeed found (Figures 7 and 8) for all subjects except Bird 104, which seemed to have poor color resolution in general. We found consistently (Figure 9) that 630 nm was more confusable with 627 nm than was 560 nm with 563 nm, indicating less color sensitivity around 630 nm than around 560 nm. It was also the case (Figure 9) that differences in confusabilities were
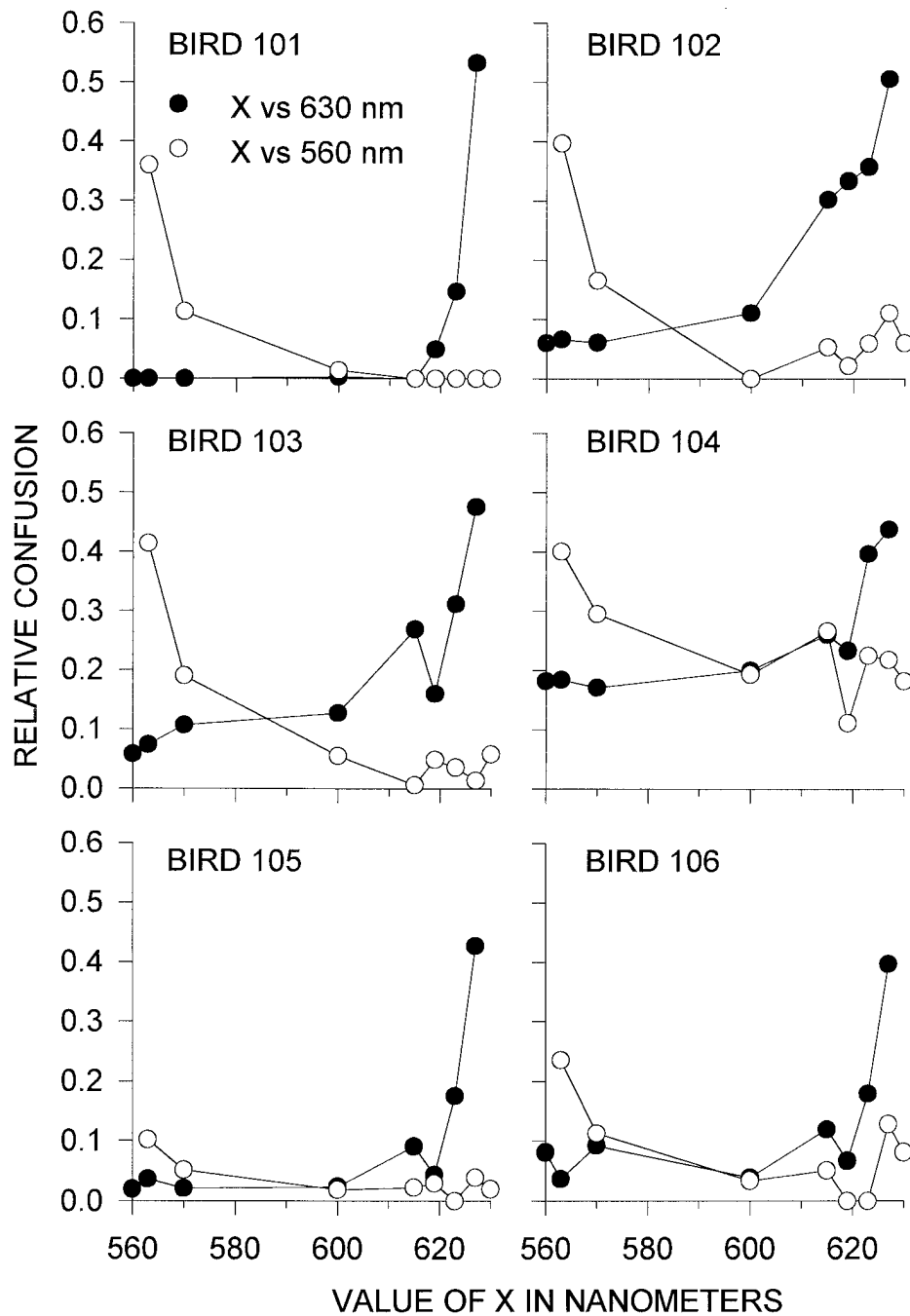
Fig. 9. Confusion indices (Equation 1) for the performance on the 560- versus X-nm and 630- versus X-nm alternatives for each individual subject as a function of the stimulus value of X. These indices were obtained from a single fit for each individual subject to all 63 data points from this experiment.
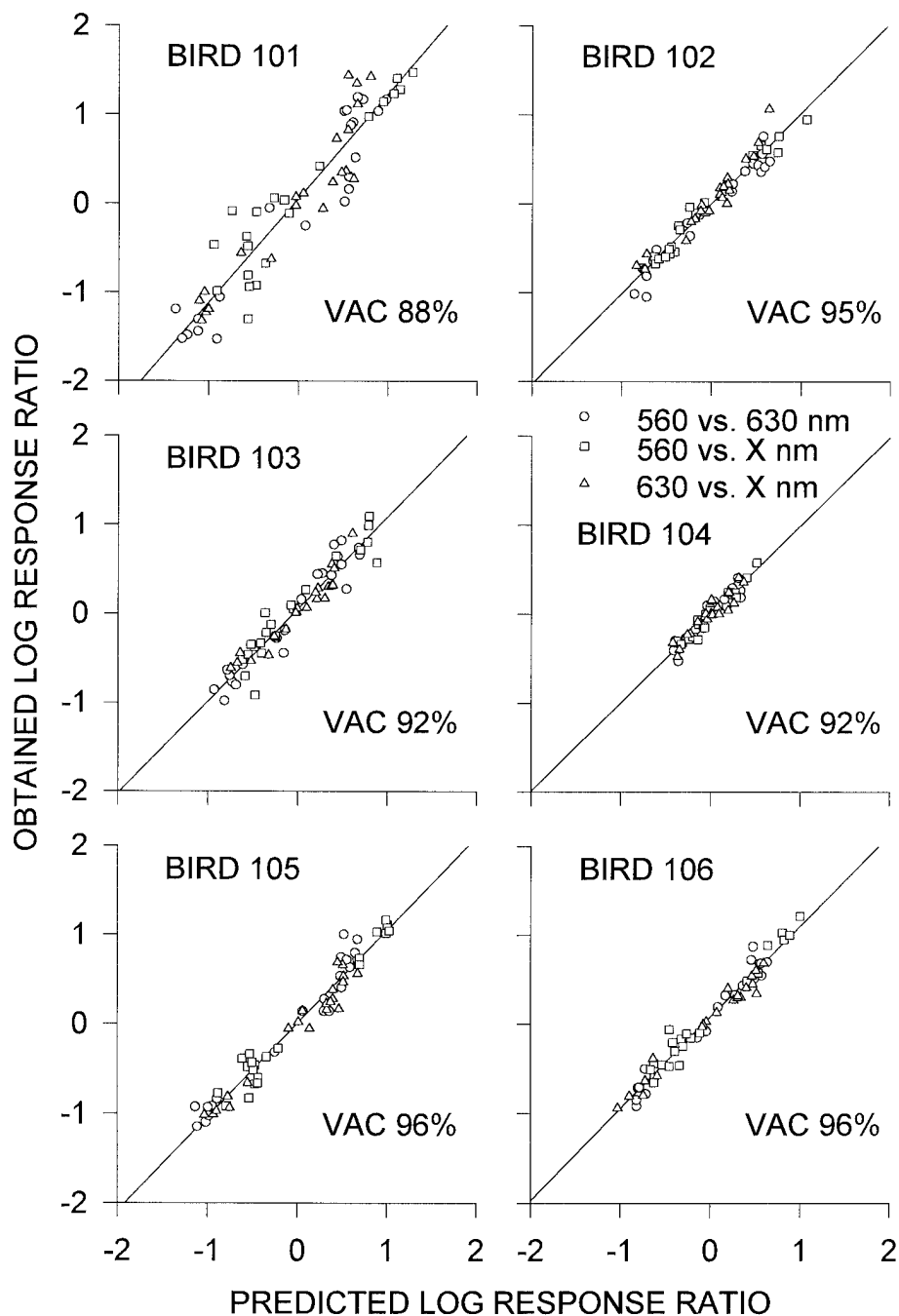
Fig. 10.   Obtained pairwise log response ratios as a function of predicted log response ratios using Equation 1 in combination with the confusion index values shown in Figure 9. The straight line is the best fitting line between the obtained and predicted data. VAC is the percentage of variance accounted for by the model with the parameters from Figure 9.
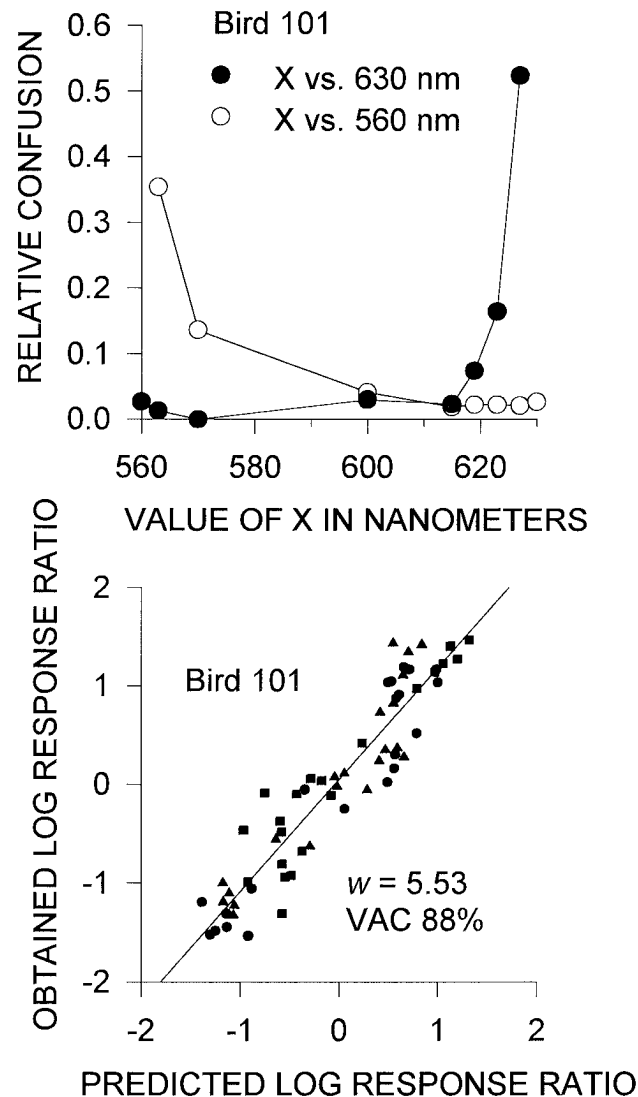
Fig. 11. Upper panel: Confusion indices (Equation 1) for the performance on the 560- versus *X*-nm and 630-versus *X*-nm alternatives for Bird 101 as a function of the stimulus value of *X*, when *w* (Equation 1) is incorporated. Lower panel: Obtained pairwise log response ratios as a function of predicted log response ratios using Equation 1 in combination with the confusion index values shown in the upper panel. The straight line is the best fitting line between the obtained and predicted data. VAC is the percentage of variance accounted for by the model with the parameters in the upper panel. Also shown is the best fitting value of *w*.

larger between 619 and 630 nm than between 560 and 570 nm for 5 out of 6 pigeons, again supporting a lower color sensitivity around 630 nm. This result is not predicted by Wright's sensitivity functions, which show a broadly similar sensitivity at both regions.

It has long been evident that stimuli that signal alternatives and the reinforcer rates in those alternatives interact to determine be-

havior allocation between alternatives (Miller et al., 1980). Initially, it was thought possible that the simple multiplication of log obtained reinforcer ratios with a sensitivity parameter (Equation 2) that measured signaling-stimulus discriminability could provide an adequate quantitative model (e.g., Miller et al., 1980; White et al., 1984). Davison and McCarthy (1994) and Alsop and Davison

(1992) showed that this approach was incorrect, and the present report confirms their conclusion by showing that no single value of sensitivity to reinforcement can account for the changing behavior allocation when stimulus conditions are varied. The interaction of stimulus confusability (or discriminability) and reinforcer rate is considerably more complex than implied by Equation 2. The present results, in conjunction with the two-alternative results of Alsop and Davison (1992) and the three-alternative results of Davison and McCarthy (1994), suggest that Equation 1 (Davison & Jenkins, 1985; Vaughan & Herrnstein, 1987) may be an effective description of behavior allocation caused by stimulus–reinforcer interaction in choice situations. It now becomes worthwhile to carry out more explicit experimental tests of this model.

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APPENDIX

Bird	Con-di-tion	Responses			Times (s)			Reinforcers			Changeovers from		
		560	630	X	560	630	X	560	630	X	560	630	X
101	53	10,170	1,246	535	5,971	1,605	1,375	149	37	11	124	251	309
	54	1,335	664	11,229	1,500	1,195	5,871	47	13	140	295	290	169
	55	555	11,305	1,686	1,043	6,704	2,233	11	145	41	262	132	249
	56	9,885	672	711	5,580	971	1,182	164	29	7	136	244	315
	57	3,456	3,911	3,025	2,946	3,995	2,474	37	10	138	372	405	212
	58	474	5,440	4,606	1,130	3,232	3,304	12	147	41	400	250	338
	59	9,428	867	992	4,987	1,234	1,375	149	41	6	170	303	338
	60	1,871	567	8,864	1,760	1,173	5,322	45	13	142	289	314	183
	61	524	14,529	655	1,018	6,774	1,031	8	148	37	294	169	268
	62	9,242	627	364	5,159	1,022	862	157	34	9	181	299	296
	63	1,053	1,876	6,803	1,475	1,892	3,337	36	9	155	365	364	250
	64	458	7,181	1,338	1,247	4,142	2,032	6	158	35	394	254	376
	65	10,605	678	359	6,551	1,011	833	157	36	7	105	242	240
	66	579	553	11,706	931	1,038	6,232	40	5	155	272	319	161
	67	363	11,037	855	824	6,008	1,330	9	163	28	268	98	250
	68	8,959	1,180	527	5,440	1,308	1,134	150	39	11	177	274	351
	69	928	637	8,059	1,342	1,348	4,790	40	11	149	272	336	143
	70	390	13,051	478	779	8,113	985	7	148	42	237	146	214
	71	5,967	534	2,271	3,730	1,011	2,179	162	31	7	158	297	324
	72	3,799	348	3,495	3,188	1,073	2,545	32	10	158	321	354	189
	73	371	12,676	480	797	6,922	881	12	156	32	238	137	271
102	53	5,449	948	940	5,294	1,067	1,172	153	40	7	178	282	319
	54	1,407	1,887	4,873	1,459	2,055	4,284	36	9	155	322	372	245
	55	912	3,996	2,781	1,039	3,254	2,537	15	152	33	333	226	312
	56	4,556	1,247	1,284	4,453	1,319	1,359	144	48	8	179	258	311
	57	1,943	3,167	2,469	2,088	3,087	2,190	34	12	154	359	394	276
	58	917	3,001	3,604	1,281	2,607	3,257	9	147	44	437	271	377
	59	4,309	1,851	943	4,066	1,889	1,261	146	46	8	178	273	240
	60	2,393	847	4,191	2,524	1,173	3,485	36	8	156	274	280	149
	61	984	5,224	1,063	1,321	5,290	1,339	10	151	39	318	148	266
	62	4,731	1,738	1,151	4,613	2,077	1,509	143	45	12	189	300	301
	63	1,762	2,331	3,420	2,236	2,966	3,415	37	9	153	353	353	250
	64	773	4,282	3,641	1,212	3,975	3,752	8	151	41	334	180	272
	65	4,324	1,894	1,134	4,270	2,011	1,529	146	42	12	134	298	304
	66	1,004	2,294	3,641	1,526	2,564	3,383	34	14	152	352	355	219
	67	643	4,193	2,672	951	3,468	2,531	11	147	42	344	222	331
	68	4,742	1,813	531	4,333	1,774	795	150	32	10	238	325	318
	69	1,324	960	5,206	1,665	1,181	5,214	43	6	149	363	354	170
	70	500	5,178	1,615	1,538	4,719	2,509	9	140	39	300	162	286
	71	2,876	1,723	2,078	2,704	1,630	2,220	147	46	7	225	330	333
	72	2,958	980	3,591	3,079	1,610	3,413	45	7	148	330	350	242
	73	499	5,582	482	1,159	5,126	1,086	5	158	37	337	160	272
103	53	3,744	1,986	1,000	2,581	1,811	1,508	148	44	8	373	471	505
	54	630	1,759	5,184	1,111	1,886	3,257	37	16	146	391	459	304
	55	421	4,050	2,113	984	2,704	1,950	9	154	37	414	307	403
	56	5,226	954	821	3,886	1,230	1,189	154	38	8	265	388	408
	57	1,303	2,465	2,351	1,676	2,275	1,973	45	10	145	518	561	374
	58	713	2,682	2,343	1,351	2,144	2,204	13	158	29	538	397	513
	59	4,584	1,048	1,033	3,397	1,555	1,716	145	37	17	316	460	502
	60	1,620	599	2,151	2,008	1,552	1,860	38	7	155	568	588	400
	61	583	3,427	952	1,500	2,743	1,730	7	142	51	534	401	507
	62	3,747	1,054	722	2,855	1,681	1,691	141	51	8	328	394	431
	63	753	1,156	2,102	1,642	2,042	2,100	38	11	151	468	550	397
	64	567	2,834	1,644	1,200	2,102	1,677	10	159	31	478	333	441
	65	5,841	884	597	4,076	1,309	1,126	147	43	10	341	455	501
	66	1,781	1,237	4,221	1,940	1,763	2,785	36	14	150	481	495	315
	67	642	2,769	1,377	1,926	2,212	1,914	11	149	36	512	365	503
	68	5,372	899	433	3,792	1,402	1,178	141	51	8	305	409	433

APPENDIX

(*Continued*)

Bird	Con-di-tion	Responses			Times (s)			Reinforcers			Changeovers from		
		560	630	X	560	630	X	560	630	X	560	630	X
	69	2,064	731	2,026	2,126	1,539	1,740	49	8	143	521	540	414
	70	586	4,204	1,307	1,291	2,953	1,597	5	156	39	479	288	417
	71	3,197	1,159	1,733	2,426	1,561	1,989	143	47	10	312	392	441
	72	2,282	496	2,023	2,130	1,446	1,759	38	4	158	491	511	362
	73	919	5,886	739	1,469	3,857	1,186	6	155	39	465	280	383
104	53	1,921	1,018	1,155	1,809	1,404	1,611	160	31	9	456	519	612
	54	1,393	1,094	1,797	1,992	1,770	1,732	37	7	155	583	566	431
	55	944	3,173	1,819	1,611	2,396	2,039	10	153	37	446	364	470
	56	2,305	1,254	1,323	2,150	1,841	1,922	152	40	8	354	464	522
	57	1,205	1,804	1,514	1,847	2,140	1,689	30	11	155	510	568	401
	58	932	1,722	1,961	1,844	1,885	2,304	8	161	31	533	376	514
	59	1,971	1,610	1,112	2,025	2,113	2,182	146	45	9	348	461	535
	60	1,524	840	1,752	1,852	1,580	1,800	43	4	153	412	486	372
	61	1,021	2,600	1,017	1,640	2,201	1,557	11	147	42	468	333	445
	62	1,975	1,288	1,272	2,019	1,789	2,014	157	37	6	395	516	559
	63	1,144	1,644	1,625	1,699	2,170	1,639	41	10	149	519	587	410
	64	798	1,496	1,522	1,681	1,612	1,863	14	154	32	574	384	527
	65	2,526	1,163	666	2,259	1,533	1,303	145	43	12	364	421	456
	66	1,218	976	2,439	1,788	1,652	2,154	36	11	152	494	500	402
	67	895	1,781	1,604	1,568	1,721	1,985	12	146	40	655	489	620
	68	2,602	1,021	1,018	2,303	1,395	1,553	157	36	7	400	463	590
	69	1,206	870	2,624	1,751	1,434	2,163	26	14	160	524	529	361
	70	786	2,019	1,514	1,477	2,032	1,904	9	151	40	514	355	478
	71	1,408	961	1,171	1,809	1,739	1,932	159	36	5	426	544	548
	72	1,439	734	1,237	1,930	1,557	1,735	41	16	143	551	589	503
	73	788	1,645	719	1,517	1,720	1,413	2	159	39	544	382	518
105	53	4,202	970	402	3,913	2,011	1,497	153	38	9	237	351	357
	54	763	553	3,606	1,436	1,780	3,556	43	9	148	329	410	225
	55	395	3,322	968	1,435	3,592	2,016	7	160	33	404	262	393
	56	3,889	741	708	3,415	1,443	1,533	149	40	11	233	362	362
	57	1,183	2,461	2,768	1,806	3,281	2,700	36	3	161	362	439	261
	58	332	2,750	1,964	1,361	2,667	2,398	7	144	49	408	266	338
	59	5,580	987	516	4,844	1,751	1,462	147	43	10	260	367	406
	60	1,933	559	5,827	2,126	1,521	4,154	35	10	155	333	350	231
	61	505	4,330	1,467	1,492	3,677	1,936	10	147	43	396	263	359
	62	6,903	773	535	4,695	1,327	1,454	155	34	11	213	331	395
	63	1,335	965	4,405	1,765	1,968	3,287	41	10	149	400	406	242
	64	374	5,232	3,107	1,122	3,195	2,927	7	151	42	359	219	376
	65	6,039	595	407	4,524	1,367	1,252	149	42	9	268	357	456
	66	1,029	401	4,115	1,654	1,500	3,589	47	9	143	328	371	267
	67	343	4,265	925	1,202	3,933	2,125	10	150	40	388	224	379
	68	4,096	650	368	3,889	1,464	1,436	157	32	11	315	455	497
	69	606	437	4,110	1,678	1,339	4,069	39	14	146	441	449	339
	70	347	3,691	749	1,569	4,515	2,111	11	142	47	416	256	398
	71	3,168	603	681	3,835	1,955	2,103	151	36	12	248	390	445
	72	650	345	2,979	1,846	1,787	4,175	36	18	146	361	388	268
	73	441	3,025	824	1,340	4,630	1,879	15	157	28	339	225	367
106	53	4,249	798	396	4,939	1,669	1,494	149	41	10	188	270	283
	54	1,241	795	3,424	2,478	2,210	3,615	28	6	166	300	347	192
	55	655	3,384	1,315	2,025	3,681	2,482	7	153	38	328	193	273
	56	3,058	865	808	3,650	1,852	2,198	158	37	5	152	276	334
	57	1,092	1,536	1,548	2,910	3,143	2,479	37	8	152	374	423	270
	58	590	2,278	1,679	2,242	2,822	2,794	8	151	37	346	199	307
	59	2,383	779	307	3,375	3,180	2,525	135	35	9	167	288	304
	60	1,583	750	1,817	3,428	2,510	2,988	31	15	146	375	377	235
	61	588	3,008	860	2,471	4,201	2,800	6	148	36	269	183	252
	62	3,541	735	395	4,632	2,731	2,343	136	29	17	187	306	297

APPENDIX

(*Continued*)

Bird	Con-di-tion	Responses			Times (s)			Reinforcers			Changeovers from		
		560	630	X	560	630	X	560	630	X	560	630	X
	63	889	1,057	3,991	2,259	2,492	3,930	34	4	161	240	265	137
	64	688	2,175	1,103	2,535	3,203	3,019	11	145	37	353	234	356
	65	4,141	554	250	5,514	1,719	1,652	148	39	12	156	269	266
	66	1,141	538	3,360	2,341	2,069	4,196	48	12	136	308	361	235
	67	351	2,887	1,013	1,743	3,259	2,356	9	154	37	314	173	300
	68	3,335	694	332	4,184	2,098	1,909	157	28	13	198	361	357
	69	1,096	405	3,518	2,735	2,089	4,478	30	6	158	244	289	158
	70	415	2,932	732	2,460	4,333	2,600	8	147	37	343	218	295
	71	2,949	908	963	3,460	2,893	2,953	159	26	7	160	323	319
	72	1,710	343	2,192	3,139	1,753	3,049	44	7	149	313	332	230
	73	494	2,989	616	2,538	4,173	2,408	8	149	36	273	154	260